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Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements

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A B S T R A C T

This paper presents and optimizes the annual heating, cooling and lighting energy consumption associated with applying different types and properties of window systems in a building envelope. Through using building simulation modeling, various window properties such as U-value, solar heat gain coefficient (SHGC), and visible transmittance (Tvis) are evaluated with different window wall ratios (WWRs) and orientations in five typical Asian climates: Manila, Taipei, Shanghai, Seoul and Sapporo. By means of a regression analysis, simple charts for the relationship between window properties and building energy performance are presented as a function of U-value, SHGC, Tvis, WWR, solar aperture, effective aperture, and orientation. As a design guideline in selecting energy saving windows, an optimized window system for each climate is plotted in detailed charts and tables.

1. Introduction

Globally, buildings are responsible for between 30 and 40 percent of all primary energy use, greenhouse gas emissions, and waste generation [1]. Lighting, heating, and cooling represent most of the total energy use in a typical building. In resident buildings, heating is the largest consumer of energy; on the other hand, for commercial buildings, lighting is the dominant consumer [2]. The amount of energy consumed through heating, cooling or lighting in a building is mainly influenced by its fenestration system. Of several products in the system, windows, which can provide light, view and fresh air to the resident, play the most important role in a building's energy consumption. Since the overall heat transfer coefficient (or U-value) of windows is normally five times greater than those of other components of a building's envelope (e.g., walls, doors, etc.), and about 20–40% of energy in a building is wasted through windows [3], the design and selection of a proper window system is one of the important strategies for effectively conserving the energy of a building [4].

In a glazing system, façade-related properties, such as U-value, G-value, shading, daylight factor, and light control, influence a building's energy consumption [5,6]. Recently, much research has been conducted into the effect on building energy load reduction and on human comfort levels of applying low emissivity coating, gas fills and spacers in glazing [7–9]. In terms of window performance properties, the solar heat gain coefficient (SHGC) in a glazing is connected with heating and cooling energy consumption, the visible transmittance (Tvis) affects the lighting energy load, and a light-to-solar-gain ratio (LSG) chart is applied to indicate the value of the relationship between SHGC and Tvis [10–13]. As a compound term, solar apertures and effective apertures are represented by the SHGC multiplied by the window wall ratio (WWR) and the Tvis multiplied by the WWR, respectively [6]. There are methods currently available that allow easy determination of the benefits and the handicaps of a glazing system choice given the complex correlation between the window performance properties.

As a result, many researches, papers, theses and books about window systems have been published recently. However, previous studies have focused only on a particular envelope component and region and issues of glazing applications in building facades that are connected with problems like overcooling, overheating, glazing and lack of visual comfort. In the case of US climates, several researches related to glazing systems have been performed by varying glazing performance properties [14,15], and numerical analyses of glazing in European climates have also been conducted [16,17]. However, those papers focused solely on a particular region

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Table 1
Variables and outputs for simulation.

	Variables	Output
Glazing selection	A/B/C/D/E/F	Heating
Glazing type	Double/Triple	
WWR (%)	100/75/50/25	Cooling
Orientation	S/N/E/W	
Climate	Manila/Taipei/Shanghai/Seoul/Sapporo	Lighting

or certain types of building energy (heating, cooling, or lighting energy). For Asian regions, there is a limited amount of research related to windows and their effect on building energy, with what research there is being focused on comfort conditions for building occupants [18].

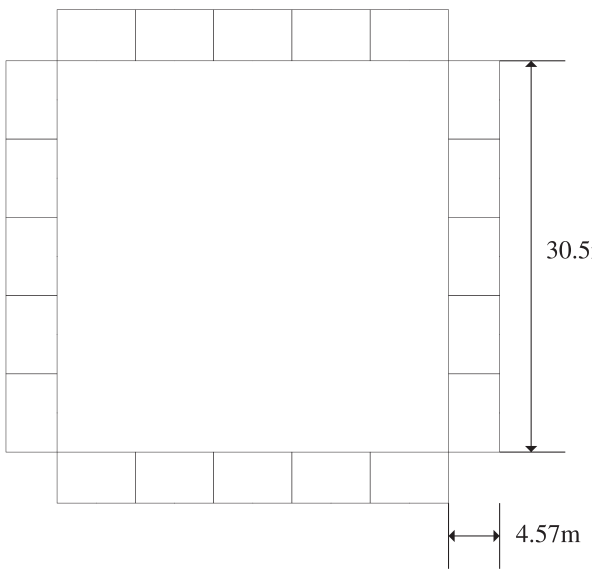

Fig. 1. Plan view of prototypical building module.

Thus, the starting point of this study is to develop simple charts of building energy consumption related to the window properties (i.e., WWR, U-value, Tvis and SHGC) and according to variations of climate, especially in Asian regions. In addition, optimized WWR and window performance properties are tested in each climate condition by building type and orientation. Through these performance evaluations, the optimal window performance properties in Asian regions can be plotted and proposed.

2. Methodology

This section describes the methodology used in this study to find the optimal window system for reducing building energy loads. The simulation variables and outputs are shown in Table 1. For input data, variations are chosen based on two main factors: climate change (Asian regions) and window properties (orientation, WWR, U-value, SHGC, and Tvis). As the output data, building energy consumption consists of 3 elements: heating, cooling and lighting loads.

The analysis procedure is as follows:

1) Set the building module and envelope properties for the input data
2) Classify the Asian climate into 5 categories
3) Select 6 glazings and construct double and triple window systems with variations of glazing
4) Conduct a data analysis based on the overall energy consumption output data related to the categories of orientation and WWR
5) Construct a chart of the simulated data by heating, cooling and lighting loads and by variation in U-value, SHGC, and Tvis
6) Optimize the window system properties, locations and relative ratios for Asian buildings

2.1. Simulation and input data

To evaluate the appropriate performance criteria for glazing systems in buildings, a computer simulation tool for the design and selection of fenestration systems is used. It calculates heating, cooling and lighting energy use, peak energy load demand, and occupant

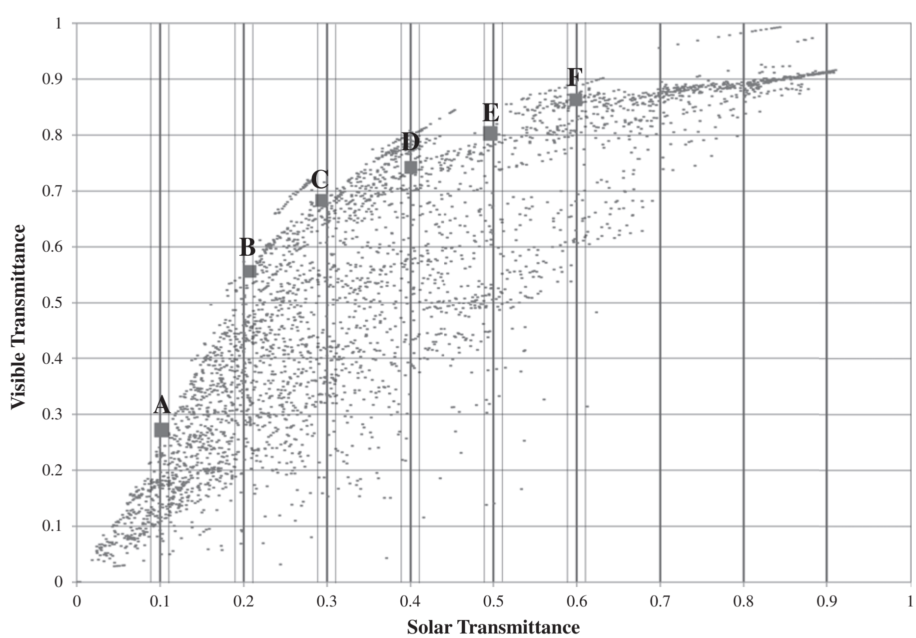

Fig. 2. Input variables as glazing performance properties.

Table 2
The window system properties used in simulation.

Window	Type	SHGC	Tvis	LSG	U-factor ($W/m^2 \cdot K$)	NFRC ID
#1	Double layer	0.175	0.248	1.47	1.501	5021
#2	Double layer	0.249	0.49	1.96	1.507	2172
#3	Double layer	0.313	0.6	1.91	1.503	3088
#4	Double layer	0.389	0.654	1.68	1.539	5034
#5	Double layer	0.475	0.711	1.49	1.503	2211
#6	Double layer	0.564	0.753	1.33	1.504	4017
#7	Triple layer	0.135	0.22	1.62	0.795	5021
#8	Triple layer	0.209	0.433	2.07	0.797	2172
#9	Triple layer	0.277	0.53	1.91	0.796	3088
#10	Triple layer	0.332	0.577	1.73	0.805	5034
#11	Triple layer	0.41	0.627	1.52	0.795	2211
#12	Triple layer	0.492	0.664	1.34	0.796	4017
Low-E glass	–	Tsol: 0.706	0.87	–	–	1209

comfort for windows in buildings. Commercial Fenestration/Façade Design Tool (COMFEN) based on energy plus engine data and advanced by Lawrence Berkeley National Laboratory (LBNL) is a reliable method for comparing window system energy usage [19,20].

The simulated building is made up of 4 perimeter zones consisting of 5 office modules each, and each office module consists of a zone 4.57 m (15 ft) deep by 6.1 m (20 ft) wide, with a floor-to-floor height of 3.05 m (10 ft). The office module is shown in Fig. 1. And, the values of U-factor, lighting load and equipment load are set to the default values of COMFEN [19]. An aluminum frame with a thermal break, a U-factor of 5.68 W/m^2 K and a width of 57.2 mm is applied. In the HVAC system, the lighting load is 10.76 W/m^2, the equipment load is 8.07 W/m^2, and the lighting control mode is set as continuous. The U-factor data of other elements such the walls, floor and roof (2.05–3.17 W/m^2 K) are inserted based on climate figures addressed in ASHRAE Standard 90.1-2010 [21].

2.2. Optical property for glazing system

A glazing system is defined parametrically to facilitate an understanding of its effects on energy performance. The glazing area is varied using window wall ratios (WWRs) corresponding to 0%, 25%, 50%, 75% and 100% of the wall area. By ASHRAE Standard 90.1-2010 [21], the SHGC value requirement of a vertical window system extends from 0.25 to 0.45. Thus, based on the Pareto Frontier for high LSG to maximize energy efficiency, 6 glazing types were selected from the National Fenestration Rating Council (NFRC) database and addressed as A to F in Fig. 2. As shown in Fig. 2, those 6 points are chosen by maximum Tvis values in 10% ranges of fiducial line which ranges of 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 of Tsol. Also, the corresponding NFRC ID of each glazing type is listed in Table 2. These glazings covered a range of Tsol (0.1–0.79), Tvis (0.1–0.89), LSG (0.3–1.92) and U-value (5.5–5.9 W/m^2 K) levels that are representative of currently available products, and are shown in Fig. 2.

Using the 6 selected types of single glazing, window systems were constructed with center-of-glass U-factors of 1.501–1.539 W/m^2 K, a target that can be achieved using two layers of glass and an argon fill. Using three layers of glass, other window systems were constructed with similar features and center-of-glass U-factors of 0.795–0.805 W/m^2 K. The window systems have the combination of a selected glazing on the outside and two other low-E glasses which are located inside from the center. Those two ranges of U-factor values are based on the data from 2009 ASHRAE Handbook [22].

The properties of the low-E glass are as follows: Tsol = 0.706, Tvis = 0.87, and an argon gas fill of 12.7 mm thickness. The combined performance properties of the window systems used for the simulation are shown in Table 2.

2.3. Climate data

Climate data is one of the important variables to calculate building energy consumption, and is well defined by ASHRAE standards. Each categorized zone is also divided by thermal criteria that are related to cooling and heating days.

First of all, according to climate classification of ASHRAE Standard [21], Asian climate distribution ranges from zone 1 to 5. In order to cover all the climate zones in Asia, therefore, five cities which are one of the biggest metropolises in each climate zone were selected as prototypes for the building energy simulation. The chosen five cities are as follows: Manila (the Philippines) for zone 1,

Fig. 3. Case study locations in East Asia.

Table 3
Basic information of five climates; climates classification, location and solar radiation.

	Manila	Taipei	Shanghai	Seoul	Sapporo
ASHRAE climate	1A	2A	3A	4A	5A
Koppen classification	Af	Cfa	Cfa	Dfa	Dfa
Longitude (°)	121.00	121.55	121.45	126.55	141.19
Latitude (°)	14.52	25.07	31.23	37.42	43.2
Yearly statistics for direct solar radiation (W h/m^2)	18190	27254	33532	25049	22178

Taipei (Taiwan) for zone 2, Shanghai (China) for zone 3, Seoul (Republic of Korea) for zone 4, and Sapporo (Japan) for zone 5. Details of the locations are specified in Fig. 3.

Basic information of five chosen cities such as climate classification, location, cooling and heating degree-days (CDD and HDD) and direct solar radiation is provided in Table 3 and Figs. 4 and 5. According to the annual cooling and heating degree-days (CDD and HDD), cooling is dominant in Manila, which is numbered by ASHRAE standards as 1, and heating is dominant in Sapporo, which is numbered as 5. Under conditions of direct normal solar radiation, Manila has a low direct solar radiation level of less than 20 kW h/m^2 per year, whereas radiation in all other locations is greater than 20 kW h/m^2.

3. Results and discussion

In this section, the simulation results for all five cities (i.e., Manila, Taipei, Shanghai, Seoul, and Sapporo) with variously distributed glass areas in window wall ratios (i.e., 25%, 50%, 75% and 100%) as well as 12 glass types are provided and discussed.

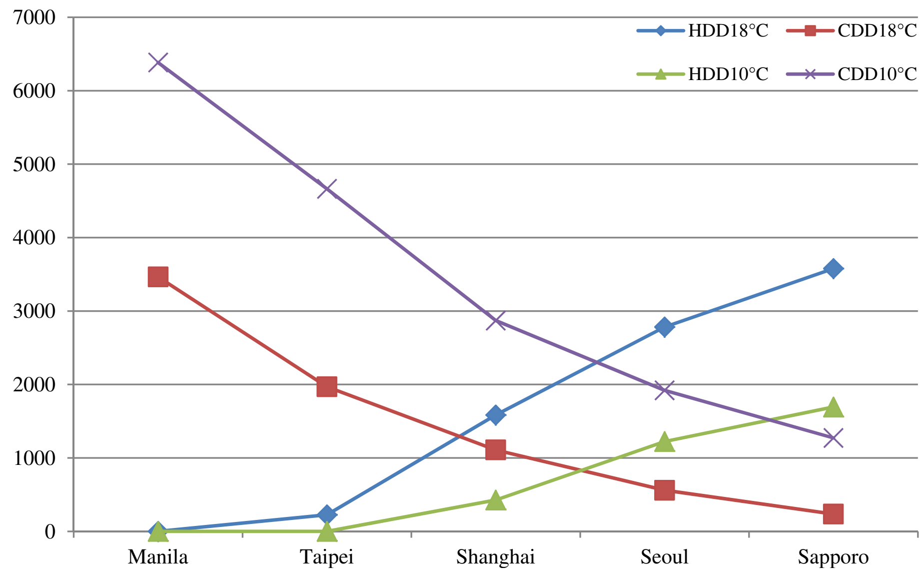

Fig. 4. Basic information of five Climates: HDD and CDD.

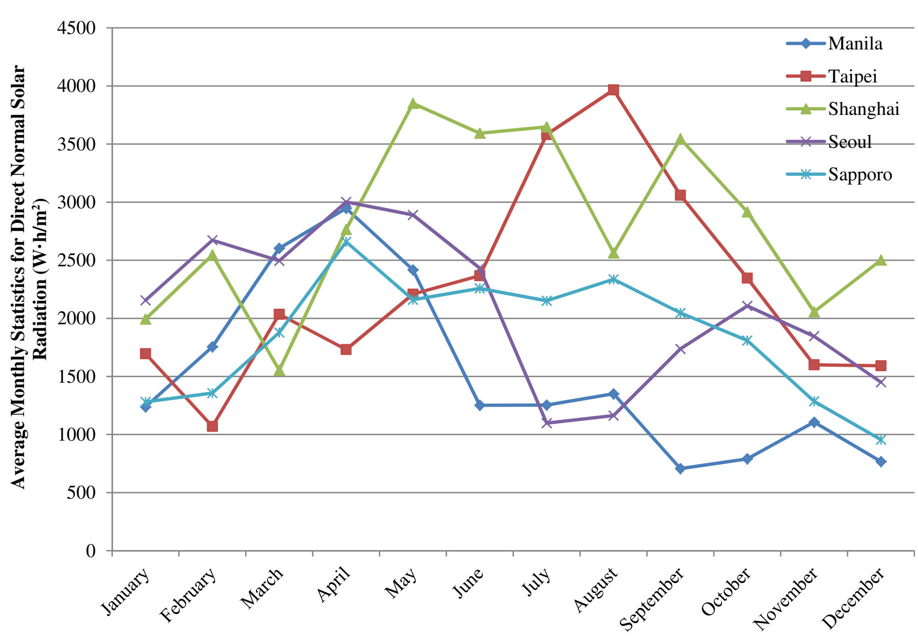

Fig. 5. Average monthly statistics for direct normal solar radiation.

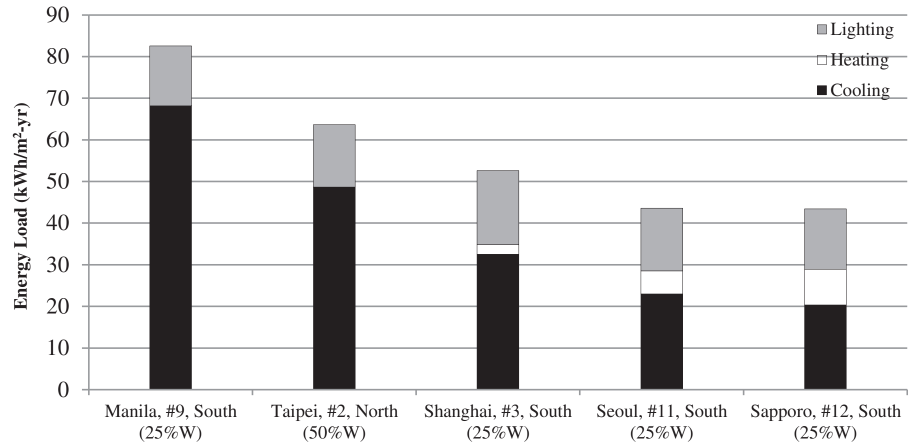

Fig. 6. Best performance of individual window system in building module.

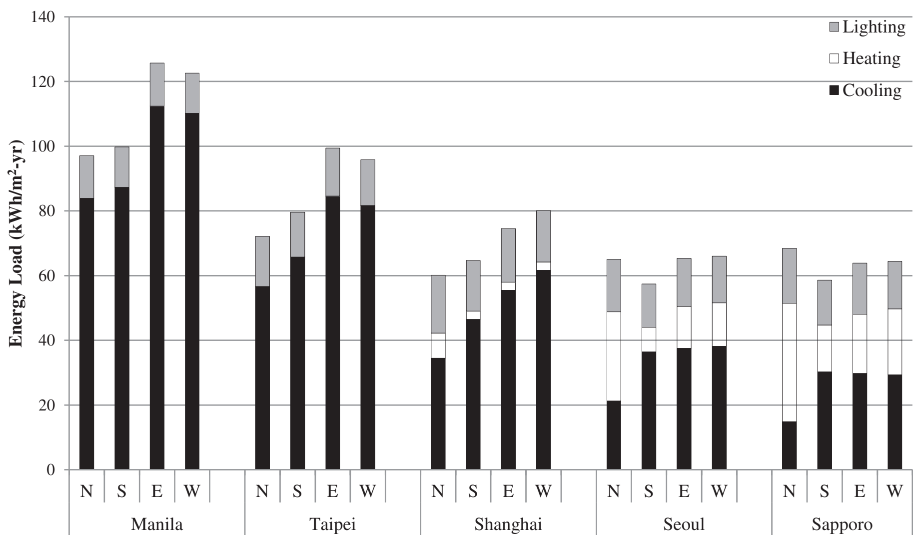

Fig. 7. Effect of orientation change on building energy consumption in five climate conditions.

3.1. Best performance window system as building module

The best performances for individual window systems in the five tested climates and according to varying window properties are indicated in Fig. 6. In general, from ASHRAE climate 1 to 5, overall energy consumption seems to be decreasing, but the lighting energy load has the least change among building energy measurements. According to installation effect, in the 4 cities other than Taipei, positioning a 25% WWR window in the south face appears to be effective. In terms of window properties, each window system has its own optimized performance. Overall, for the spectrum of hot climate to cold climate, having a higher SHGC value, which offers an advantage in heating energy, seems to be beneficial for a window system.

3.2. Orientation effect

Building energy use is affected by orientation changes, as window systems may be mounted in the north, west, east and south faces of a building. The results by orientation and climates are shown in Fig. 7. In cooling dominated cities such as Manila, Taipei and Shanghai, the north face is an efficient location to mount a window system for energy savings. Solar heat gain occurring during the main operating times in a commercial building increases cooling loads, and so the north face, which allows relatively low solar heat gain, seems to be a beneficial window location. On the other hand, in cities such as Sapporo and Seoul where both heating and cooling are concerns, installing the window in the south face can reduce the total energy load because solar heat gain has a positive effect by increasing the indoor temperature in heating season.

Table 4 shows the statistical property results for the summed energy load by orientation. According to the data, the window module installed in the south façade of the building has the lowest energy load and that in the east face has the highest energy load.

Table 4
Statistical properties by orientation variation.

Orientation	North	South	East	West
Sum (kWh/m^2-yr)	17778	17640	21017	21020
Samples	245	245	245	245
Average	72.5	71.7	85	84.7
Std	16	20.7	31.4	30.5
Max (kWh/m^2-yr)	141.3	147.4	217.5	215.1
Min (kWh/m^2-yr)	54.1	43.3	50.8	50.3

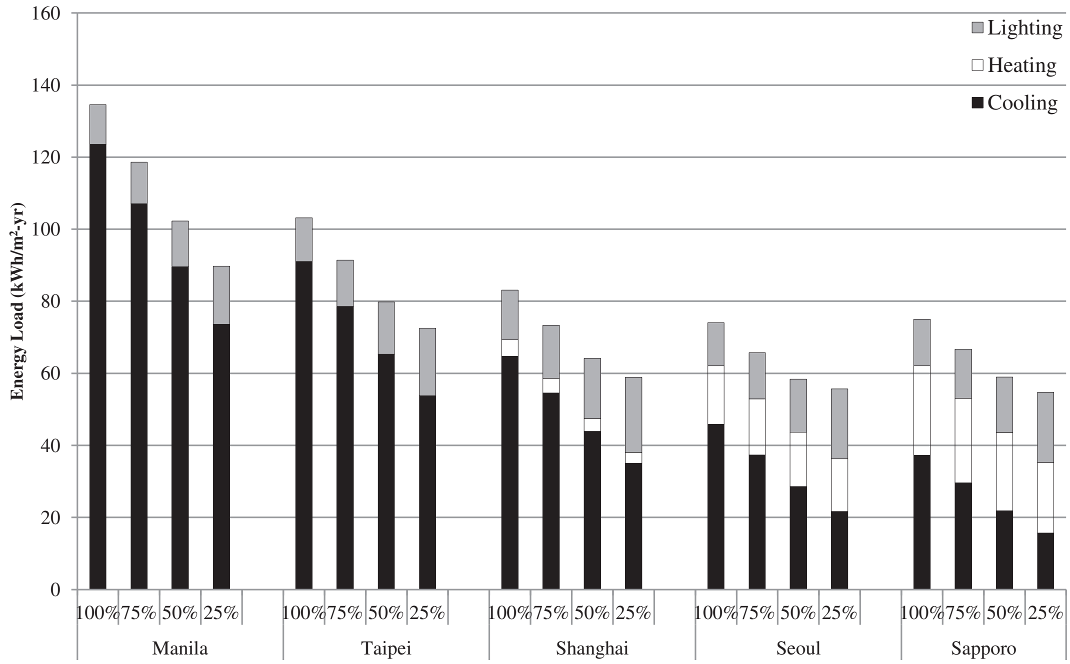

Fig. 8. Effect of WWR change on building energy consumption in five climate conditions.

Table 5
Statistical properties by WWR variation.

WWR	100%	75%	50%	25%
Sum (kWh/m^2-yr)	23022	20373	17814	16244
Samples	245	245	245	245
Average	93.9	82.8	72.1	65.5
Std	32.7	26.3	19.6	14.2
Max (kWh/m^2-yr)	217.5	181.8	142.2	105.3
Min (kWh/m^2-yr)	50.1	46.4	44.3	43.3

Looking at variance and standard deviation, the north façade shows the least variation, which means that the north is less affected by WWR, SHGC and Tvis. However, for the east and west façades, the dispersion from the average is relatively large, which indicates the results are spread over a large range of values. This means careful consideration is needed when a window system is intended to be installed on the east or west side of a building.

3.3. Window wall ratio (WWR) effect

Selecting window size is one of the important issues for a window system, not just for design purposes, but also when considering energy performance. In Fig. 8, the results shows that, as window sizes narrow by 25% for each envelope, the overall building energy load similarly decreases. In terms of lighting energy load, a small WWR increases the load. For cooling load, reducing the relative window size definitely reduces the cooling energy consumption. However, in Seoul and Sapporo, WWR hardly reduces the heating energy load because conduction loss and solar heat gain through the window are in conflict.

Table 5 shows the statistical properties for the summed energy load data by WWR. According to the data, use of a wider window results in greater energy consumption variation, by variance and standard deviation. A wide window has a proportionally large amount of façade area, and the overall building energy use

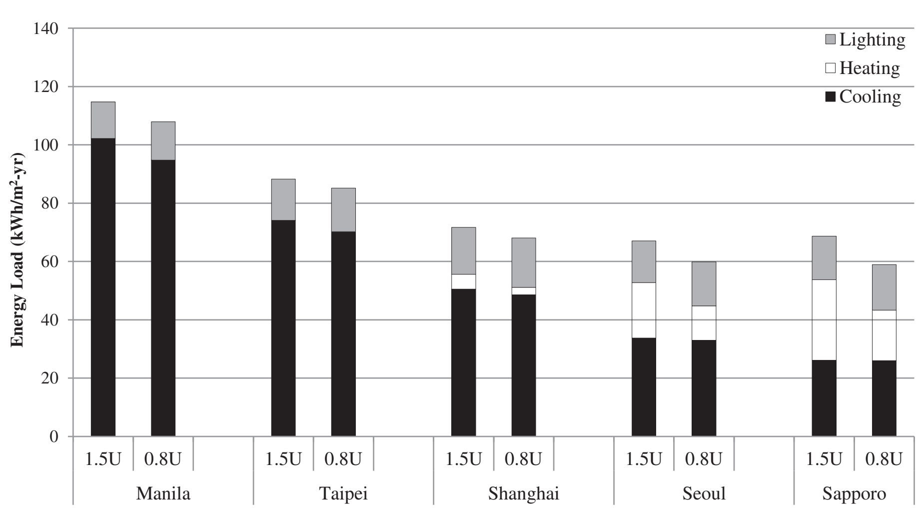

Fig. 9. Effect of U-value change on building energy consumption in five climate conditions.

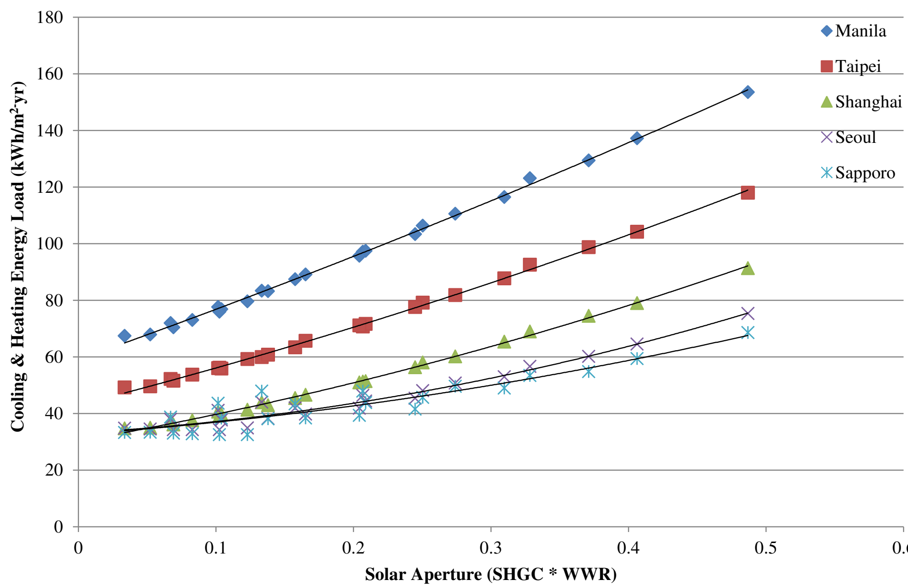

Fig. 10. Expected annual heating and cooling energy usage as a function of solar aperture.

fluctuates according to window system properties such as SHGC and Tvis. Thus, when window systems are designed for commercial or residential buildings, the fact that energy performance is related to window size and window system properties must be considered.

3.4. U-value effect

The effect of window conductance variations by U-value change is shown in Fig. 9. The reduction ratio of the cooling energy load is a low of 0.7% for Sapporo and a high of 7% for Manila. However, the reduction ratio of the heating energy load is a low of 37% for Sapporo and a high of 49% for Shanghai. According to the simulation result, in a sufficiently insulated window system, U-value changes from 1.5 W/m^2 K to 0.8 W/m^2 K have a much greater effect in reducing heating energy load than cooling energy load. Thus, for cold areas where the heating energy load is of great importance to the building energy, there is more advantage in the adoption of low U-value window systems.

3.5. Effect of SHGC on heating and cooling load

A simple chart showing incremental annual heating and cooling energy consumption as a function of solar aperture is plotted in Fig. 10. In general, when the ratio of SHGC to WWR value increases, the summed building energy load for heating and cooling is increased.

A high SHGC means that the building gets a considerable amount of solar heat gain through its window system, which has a positive effect in the winter season through heating energy reduction but a negative effect in the summer season for cooling energy reduction. However, the gap in relative intensification factor between the heating and cooling energy load is significant. At least in the 5 Asian regions chosen for this study, which have different climatic characteristics, a lower SHGC value is advantageous in heating and cooling load consumption. Thus, as can be seen in the chart, heating and cooling energy consumption increases by a quadratic polynomial curve with increasing solar aperture. By

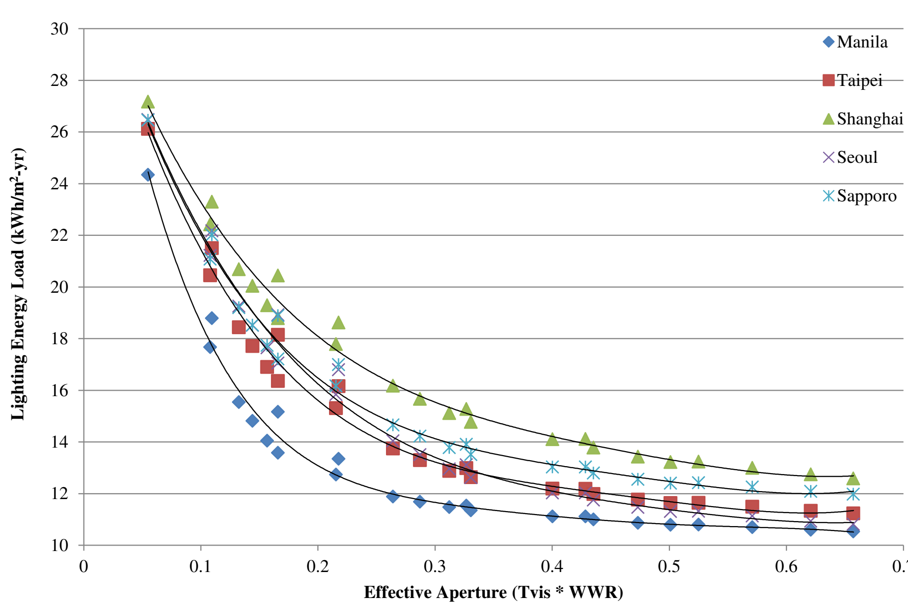

Fig. 11. Expected annual lighting energy usage as a function of effective aperture.

reference to that chart, the energy consumption and saving strategy can be defined by the solar gain performance and particular window system and/or sizes.

3.6. Effect of Tvis on lighting energy load

A simple chart displaying incremental annual lighting energy consumption as a function of effective aperture is plotted in Fig. 11. In general, when the ratio of Tvis to WWR value increases, the summed building energy load for lighting is increased.

The annual lighting energy load decreases logarithmically with increasing effective aperture value. Lighting load change by variation of effective aperture has the highest value for Manila and the lowest value for Shanghai. Influential factors affecting the lighting energy load include solar radiation (which can be expressed as visible transmittance), latitude, and fenestration system size. With an optimal effective aperture value of about 0.3–0.4, the reduction ratio of the lighting energy change is decreased.

3.7. Design guideline for window selection in a building

To optimize building energy load by selecting an appropriate window system and design, the top 3 performing window systems

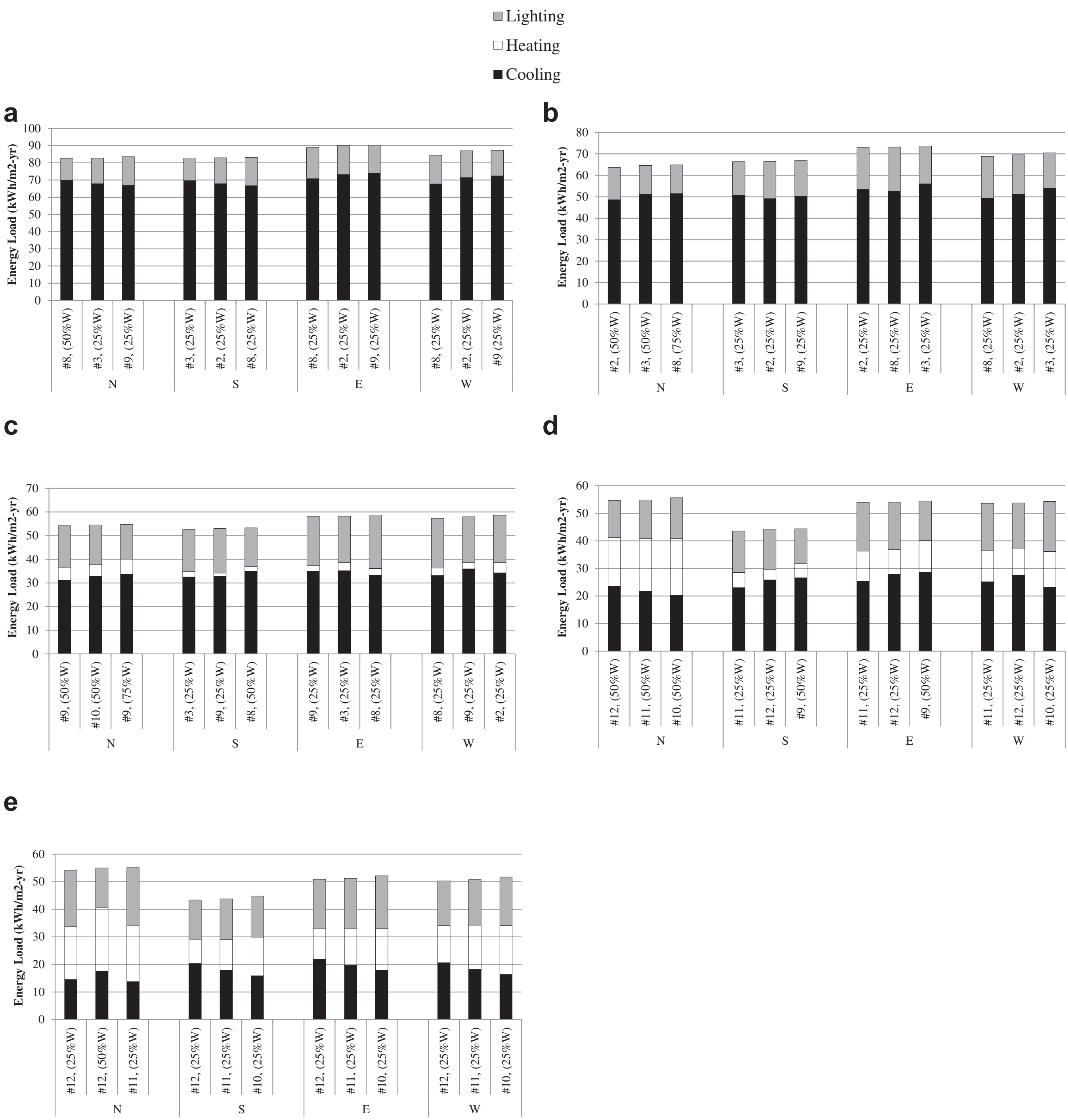

Fig. 12. Chart of top 3 performing window systems by variation of climate change: (a) Manila, (b) Taipei, (c) Shanghai, (d) Seoul, (e) Sapporo.

by variation of climate change are plotted in Fig. 12. Based on the simulation results, the following design guidelines are offered.

In the case of Manila: in orientation, installing a window system on the north face is the most energy efficient. The second, third, and fourth best options are on the south, west, and east faces, respectively. In terms of WWR, 50% WWR on the north face and 25% WWR on the south, east, and west faces are effective for energy reduction. In terms of window performance properties, the #3 window (double layer, SHGC-0.313 and Tvis-0.6) on the south and the #8 window (triple layer, SHGC-0.209, Tvis-433) on the north, east and west faces have the advantage in energy efficiency improvement.

In the case of Taipei: in orientation, installing a window system on the north face is the most energy efficient, as in the Manila case. The second, third, and fourth best options are the south, west, and east faces, respectively. In terms of WWR, 50% WWR on the north face and 25% WWR on the south, east, and west faces are effective for energy reduction. As far as window performance properties, #3 (double layer, SHGC-0.313 and Tvis-0.6) in south, the #2 window (double layer, SHGC-0.249 and Tvis-0.49) on the north and east faces and the #8 window (triple layer, SHGC-0.209, Tvis-433) on the west face have the advantage in energy efficiency improvement.

In the case of Shanghai: in orientation, installing a window system on the south face is the most energy efficient. The second, third, and fourth best options are the north, west, and east faces, respectively. In terms of WWR, 50% WWR on the north face and 25% WWR on the south, east, and west faces are effective for energy reduction. For window performance properties, the #3 window (double layer, SHGC-0.313 and Tvis-0.6) on the south, the #9 window (triple layer, SHGC-0.277 and Tvis-0.53) on the north and east faces and the #8 window (triple layer, SHGC-0.209 and Tvis-433) on the west face have the advantage in energy efficiency improvement.

In the case of Seoul: in orientation, installing a window system on the south face is the most energy efficient, as it was for Shanghai. The second, third, and fourth best options are the north, west, and east faces, respectively. In terms of WWR, 50% WWR on the north face and 25% WWR on the south, east, and west faces are effective for energy reduction. As far as window performance properties, the #12 window (triple layer, SHGC-0.492 and Tvis-0.664) on the north and the #9 window (triple layer, SHGC-0.277 and Tvis-0.53) on the south, east and west faces have the advantage in energy efficiency improvement.

In the case of Sapporo: in orientation, installing a window system on the south face is the most efficient, as in the Shanghai and Seoul cases. The second, third, and fourth best options are the north, west, and east faces, respectively. In terms of WWR, 25% WWR is effective for energy reduction for all orientations. For window performance properties, the #12 window (triple layer, SHGC-0.492 and Tvis-0.664) has the advantage in energy efficiency improvement.

According to the calculated results, each WWR and window property was optimized for greatest energy load reduction in a comparison of otherwise identical window systems. After all, in the highly insulated buildings that are recommended for ASHRAE climate zones 1 to 5, choosing the location and the relative size of windows can be a critical issue for an energy saving strategy. Therefore, through the energy charts drawn above by variables in window properties, orientation, size and building type, the data can be utilized in low energy building design or building renovation processes.

4. Conclusion

In this paper, the effect of window systems on the energy consumption of buildings in Asia has been investigated by a regression analysis in a computer simulation program. Various performance properties of window systems that can lead to energy saving buildings have been discussed for 5 typical Asian climates. According to the simulation results, the optimal configurations of window system factors such as type, size and orientation when building in Asian climates can be recommended as a design guideline.

The main findings from the simulation study can be summarized as follows:

First, the relative window size (or WWR in the building envelope) must be minimized. Except for the north face of envelopes in Manila and Taipei, a proposed lower WWR of 25% for an opaque envelope offers an advantage for the tested environments.

Second, concerning the positioning of windows, for Manila and Taipei, which are classified as ASHRAE zones 1 and 2, placement of a window system on the north face offers the highest advantage for total energy savings, followed by placement on the south, west and east faces. However, in Shanghai, Seoul, and Sapporo, which are classified as ASHRAE zones 3 to 5, respectively, the south face has the greatest advantage for total energy savings, followed by the north, west and east faces.

Third, according to the comparison of solar aperture and effective aperture, in Manila and Taipei, which have hot climates, using B and C types of window yields the best efficiency. Using C and D types of window for Shanghai, D and E types of window for Seoul, and the E type of window for Sapporo reduces building energy consumption. Thus, from hot climates to cold climates, higher SHGC and Tvis window properties are beneficial for saving energy.

Fourth, based on the U-value effect on heating and cooling energy consumption, from hot areas to cold areas, triple glazing to reduce thermal conductivity offers a performance advantage, particularly in saving heating energy.

Fifth, optimal window performance properties vary as climate change. When designing or remodeling an energy saving building, a building energy simulation process that evaluates the optimal window performance properties has to be considered.

In order to practically use the results obtained in this study, they should be properly incorporated into the older LT-Method, which has been widely adopted for lighting and thermal modeling at an early design stage. Then, designers could more effectively design theirs buildings.

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